Homogeneously sheared particle-laden turbulence in two-way coupled Eulerian-Eulerian and Eulerian-Lagrangian simulations

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NETL Multiphase Workshop 2019

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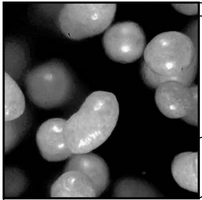
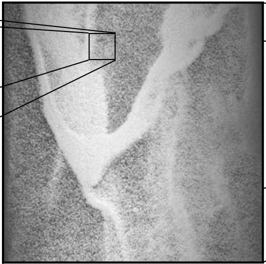
Complex and Multi-scale Collective Dynamics



Micro-scale

- L$\sim$ $O(10^{-6}\ m)$
- Simple particle motion
- Newton's 2nd law



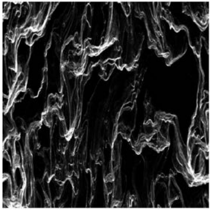
Meso-scale

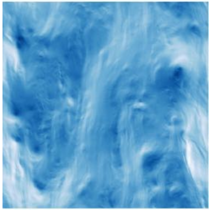
- L$\sim$ $O(10^{-3}\ m)$
- Fluid like motion
- Particles form **clusters**

Macro-scale

- L$\sim$ $O(1\ m)$
- Cluster-driven flow
- Cluster-wall interaction

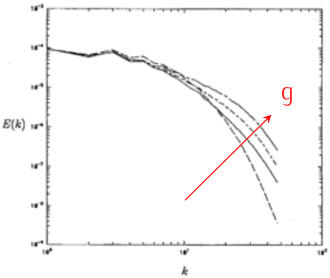
Modulation of the Suspending Turbulence





- Particles exert drag on the gas and enhance local dissipation.
- Vortex shedding by clusters.

Dispersed particles may drastically **change the structure of turbulence**



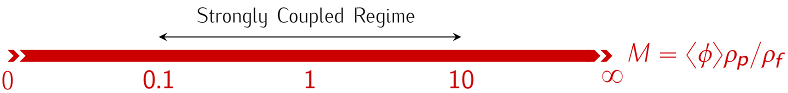
Elghobashi & Truesdell, PoF, 1993
Kasbaoui et al, JFM, 2018

Semi-Dilute Aerosols

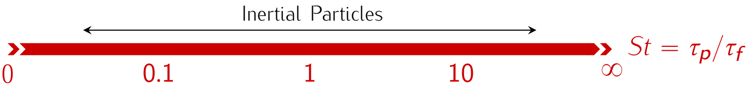
The **semi-dilute aerosols** regime

size:	$10\mu m - 500\mu m$	small heavy particles in air
volume fraction:	$\langle \phi \rangle = 10^{-5} - 10^{-3}$	
density ratio:	$\rho_p / \rho_f > 500$	

Mass loading:

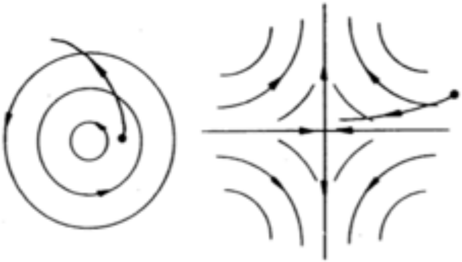


Stokes number:



Preferential Concentration

- Particles preferentially sample strain regions of the flow over vortical regions.
- Preferential concentration depends on particle inertia.



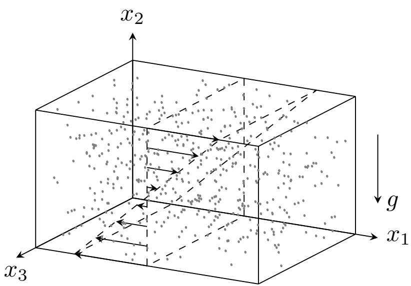
Questions:

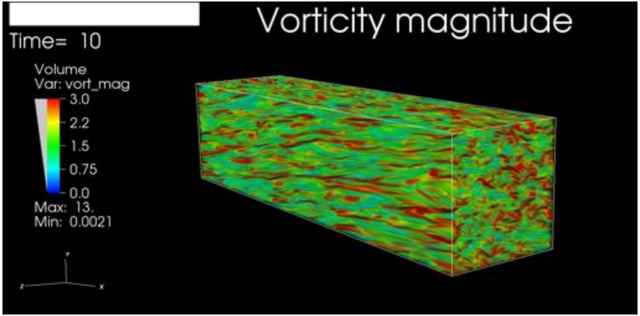
1. How do particles **modulate** the carrier phase?
2. How can we simulate two-coupled particle laden-flows in a **predictive** and **computationally efficient** way?

Kasbaoui et al, JFM, 2015
Maxey, JFM, 1987
Squires & Eaton, PoF, 1991

Homogeneously Sheared Turbulence

- Allows to study the modulation of sheared turbulence by particles without contamination from numerical turbulent forcing methods or bounding walls.
- Mimics high shear regions of more general flows.
- Single-phase HST well understood



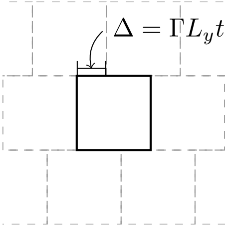


Numerical methods

Simulations of particle-laden HST rely on:

1. Implementation of a homogeneous shearing algorithm.
2. Implementation of particle-phase models.
    - Eulerian-Eulerian formalism
    - Eulerian-Lagrangian formalism

Shear Decomposition & Shear-Periodic BC



Solve for fluctuations:

$$\mathrm{U} = \Gamma y \mathrm{e}_x + \mathrm{u}$$

Navier-Stokes equations expressed for fluctuations:

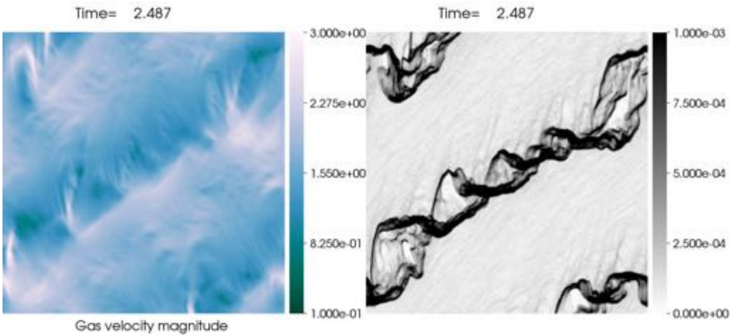
$$\begin{aligned} \nabla \cdot \mathrm{u} &= 0 \\ \rho_f \frac{\partial \mathrm{u}}{\partial t} + \rho_f \mathrm{u} \cdot \nabla \mathrm{u} + \underbrace{\rho_f \Gamma y \frac{\partial \mathrm{u}}{\partial x}}_{\text{distortion}} &= -\nabla p + \mu_f \nabla^2 \mathrm{U} + \rho_f \mathrm{g} - \mathrm{F} - \underbrace{\rho_f \Gamma u_y \mathrm{e}_x}_{\text{convection of shear}} \end{aligned}$$

With <u>shear-periodic boundary conditions</u>

$$f(x, L_y, z) = f(x - \Gamma L_y t, 0, z)$$

Kasbaoui et al, JFM, 2017

Example: Homogeneously Sheared Suspension



In the semi-dilute regime, clusters form according to the “Route-To-Clustering”:

1. Shear-activated Preferential Concentration instability
2. Particle-Trajectory crossing instability
3. Rayleigh -Taylor instability

Kasbaoui et al, JFM, 2019

Eulerian-Lagrangian Particle Solver

Integrate the equation of motion of every particle "i"

$$\frac{dx_p^i}{dt} = v_p^i$$
$$\frac{dv_p^i}{dt} = \underbrace{\frac{u(x_p^i, t) - v_p^i}{\tau_p}}_{\text{Stokes drag}} + g$$

- Simulating a few integral length scales in the semi-dilute regime, requires the tracking of $O(10^8)$ to $O(10^{10})$ particles.
- Up to $\mathbf{1.7\ 10^9}$ particles tracked in present simulations.

Capecelatro et al, JCP, 2013
Ireland et al, JCP, 2017

Euler-Euler Particle Solver: Kinetic Approach

Start from Boltzman Equation for population balance

$$\frac{\partial f}{\partial t} + \mathrm{c} \cdot \nabla_x f + \nabla_v \cdot \left(f \frac{\mathrm{F}}{m_p} \right) = 0$$

Solve for moments of the number density PDF

$$\begin{aligned}
\phi(\mathrm{x}) &= \iiint f d\mathrm{c} \quad \text{number density} \\
(\phi \mathrm{v})(\mathrm{x}) &= \iiint \mathrm{c} f d\mathrm{c} \quad \text{particle momentum} \\
\mathrm{E}(\mathrm{x}) &= \iiint \mathrm{cc} f d\mathrm{c} \quad \text{particle energy tensor} \\
\mathrm{Q}(\mathrm{x}) &= \iiint \mathrm{ccc} f d\mathrm{c} \quad \text{particle heat flux tensor} \\
\ldots
\end{aligned}$$

Williams, Phys. Fluids, 1958

Moments Transport

Conservation of number density (0th order):

$$\frac{\partial \rho_p \phi}{\partial t} + \nabla \cdot (\rho_p \phi \mathsf{v}) = 0$$

Conservation of momentum (1st order):

$$\frac{\partial (\rho_p \phi \mathsf{v})}{\partial t} + \nabla \cdot \mathsf{E} = \rho_p \phi \mathsf{g} + \frac{\rho_p \phi \mathsf{u} - (\rho_p \phi \mathsf{v})}{\tau_p}$$

Conservation of energy (2nd order):

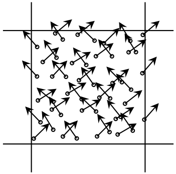
$$\frac{\partial \mathsf{E}}{\partial t} + \underbrace{\nabla \cdot \mathsf{Q}}_{\text{requires closure}} = \mathsf{g}(\rho_p \phi \mathsf{v}) + (\rho_p \phi \mathsf{v})\mathsf{g} + \frac{(\rho_p \phi \mathsf{v})\mathsf{u} + \mathsf{u}(\rho_p \phi \mathsf{v}) - 2\mathsf{E}}{\tau_p}$$

Patel et al, AiChE J., 2017
Kasbaoui et al, JFM, 2019

Presumed PDF Closure

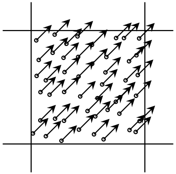
Assuming that the particle velocity distribution follows an Anisotropic Maxewellian/Gaussian:

$$f(\mathrm{x}, \mathrm{c}, t) = \frac{\phi}{(2\pi|\mathrm{P}_p|)^{2/3}} \exp\left(-\frac{1}{2}(\mathrm{c}-\mathrm{v}) \cdot \mathrm{P}_p^{-1}(\mathrm{c}-\mathrm{v})\right) \Rightarrow \mathrm{Q} = \iiint \mathrm{ccc} f d\mathrm{c} \text{ (heat flux)}$$



$\mathrm{P}_p \neq 0$

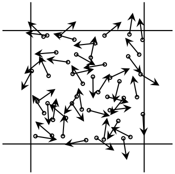
Captures particle trajectory crossing



$\mathrm{P}_p = 0$

Collapses onto a mono-kinetic distribution

$$f \rightarrow \phi\delta(\mathrm{c} - \mathrm{u}_p)$$



$\mathrm{P}_p \rightarrow T\delta_{ij}$

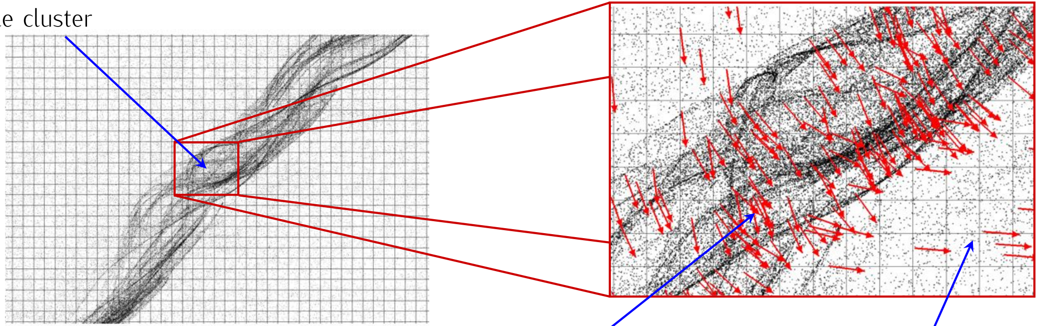
Collapses onto a Maxwellian distribution

$$f \rightarrow \frac{\phi}{(2\pi T)^{2/3}} \exp\left(-\frac{(\mathrm{c}-\mathrm{u}_p)^2}{2}\right)$$

Vié *et al*, Com. Comp. Phys., 2015

Clustering and Particle Agitation

Particle cluster



Region with **significant** particle agitation approximated by AM distribution

Region with **no** particle agitation (mono-kinetic)

Kasbaoui et al, JFM, 2019

Configuration

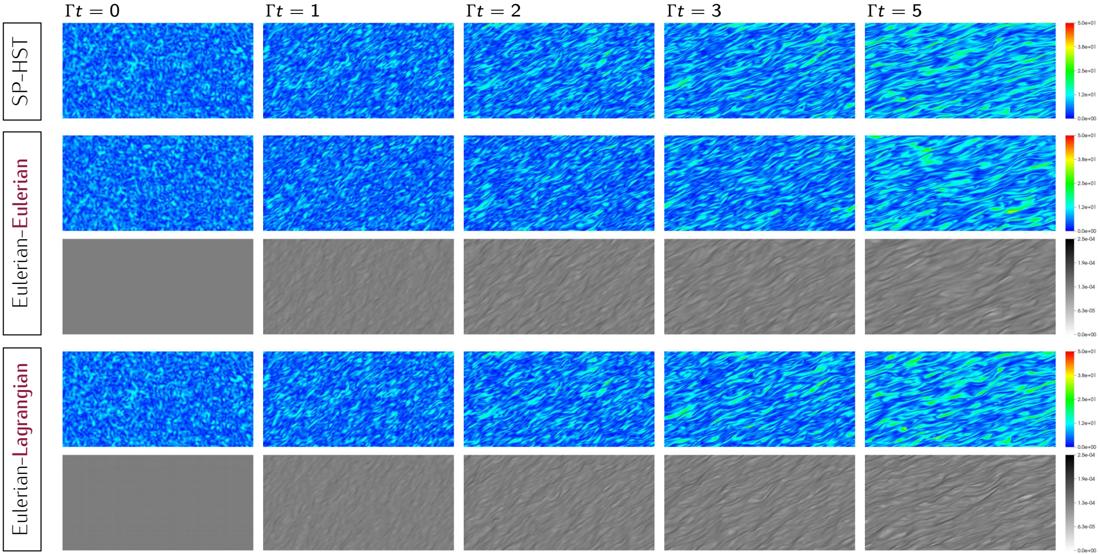
Carrier gas: air

Particles: 90μm or 50μm of density $\rho_p = 1200$kg $\cdot$ m^{-3}

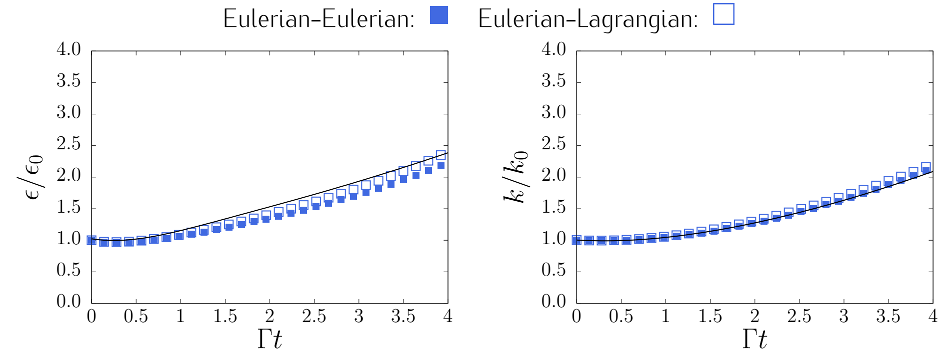
Parameter	d50L	d50H	d90L	d90H
$\langle\phi\rangle$	1.25×10^{-4}	5.0×10^{-4}	1.25×10^{-4}	5.0×10^{-4}
M	0.125	0.5	0.125	0.5
St_η	0.06	0.06	0.19	0.19
St_Γ	0.09	0.09	0.21	0.21
$\tau_p g/u_\eta$	9.4	9.4	30.4	30.4
$Re_{\lambda,0}$	29	29	29	29
S_0^*	27	27	27	27
N	0.327×10^9	1.308×10^9	0.438×10^9	1.752×10^9

- Simulations with flow solver NGA on a 512x256x256 grid.
- Both Eulerian-Eulerian and Eulerian-Lagrangian simulations conducted.

Case ($St_\eta = 0.06$, $M = 0.125$)



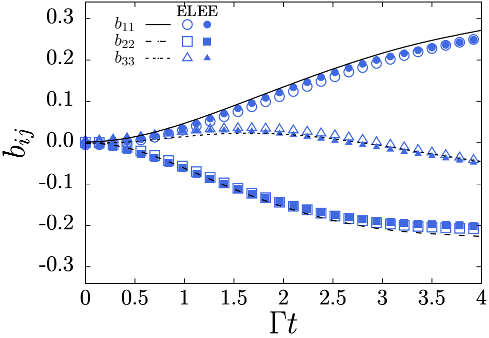
Case ($St_\eta = 0.06$, $M = 0.125$)



- TKE and dissipation rate **unchanged**.
- **No significant turbulence modulation**.

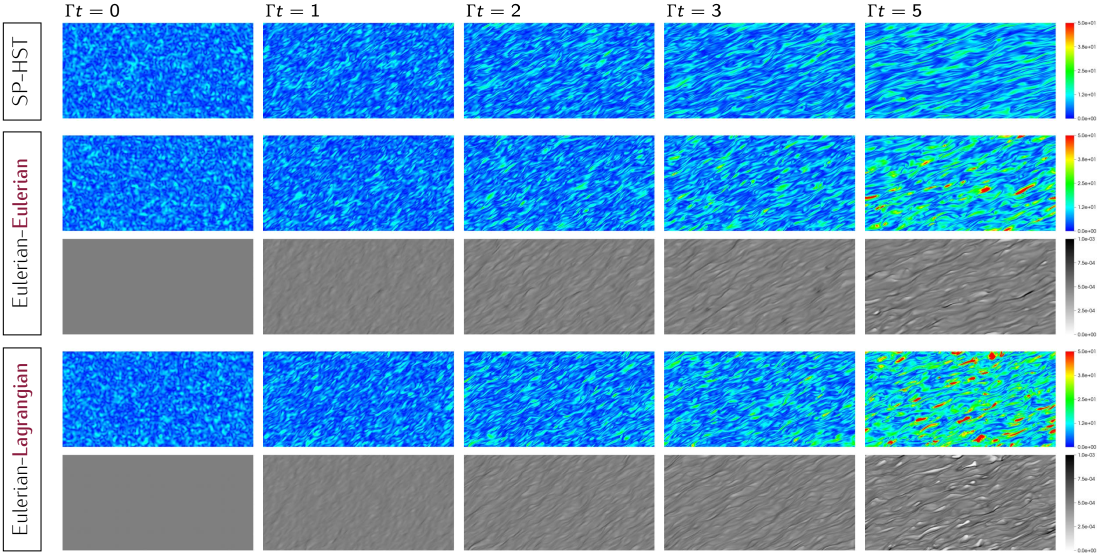
Case ($St_\eta = 0.06$, $M = 0.125$)

$$b_{ij} = \langle u_i u_j \rangle / \langle u_i u_i \rangle - \delta_{ij}/3$$

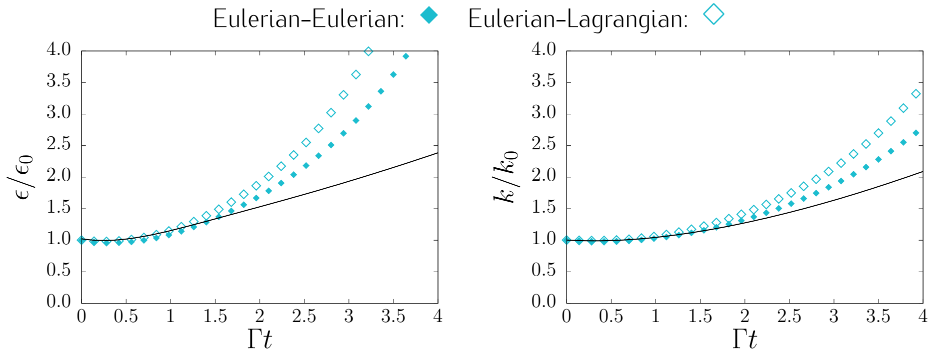


- **No change** to the diagonal components of the anisotropic Reynolds stress tensor.
- **No modification** of the flow anisotropy.

Case ($St_\eta = 0.06$, $M = 0.5$)



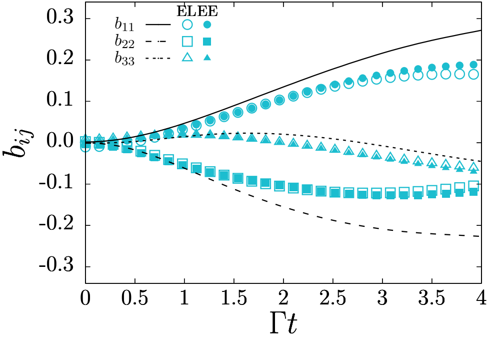
Case ($St_\eta = 0.06$, $M = 0.5$)



- **Increased** growth rates of TKE and dissipation rate.
- The dispersed phase **enhances** turbulence.

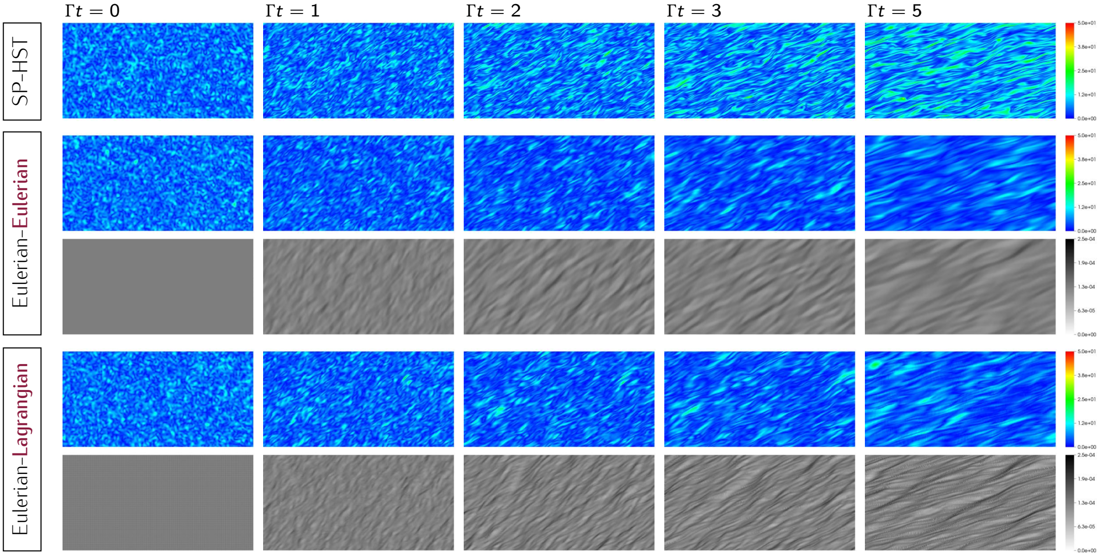
Case ($St_\eta = 0.06$, $M = 0.5$)

$$b_{ij} = \langle u_i u_j \rangle / \langle u_i u_i \rangle - \delta_{ij}/3$$

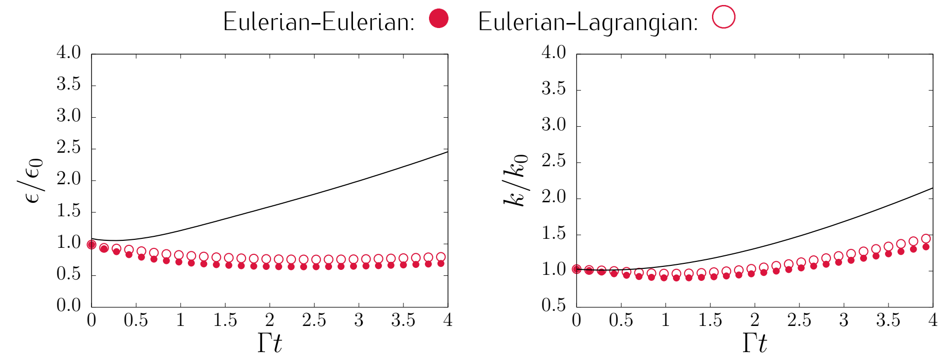


- Lower b_{11} component $\rightarrow$ vortical structures less elongated.
- Higher b_{22} component (gravity direction) due to **particle settling**.

Case ($St_\eta = 0.19$, $M = 0.125$)



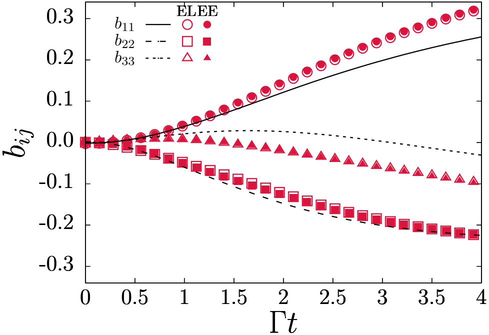
Case ($St_\eta = 0.19$, $M = 0.125$)



- **Decreased** growth rates of TKE and dissipation rate.
- The dispersed phase **attenuates** turbulence.

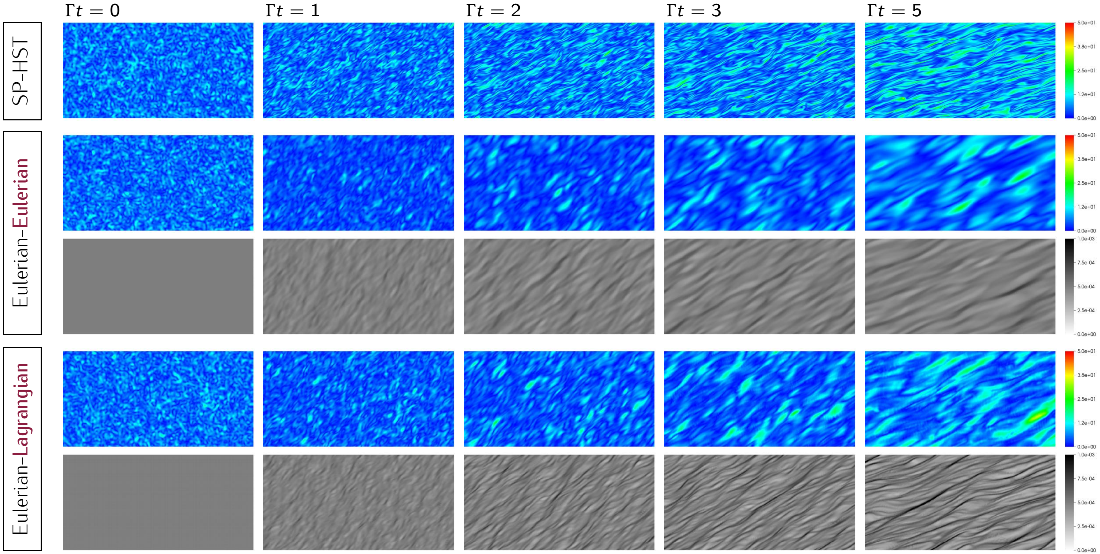
Case ($St_\eta = 0.19$, $M = 0.125$)

$$b_{ij} = \langle u_i u_j \rangle / \langle u_i u_i \rangle - \delta_{ij}/3$$

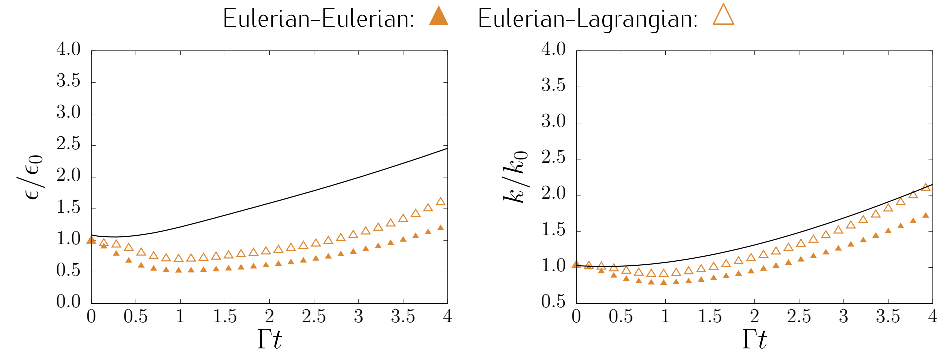


- Higher b_{11} (streamwise) component $\rightarrow$ vortical structures **more elongated** in the streamwise direction.
- Lower b_{33} (spanwise) component $\rightarrow$ turbulence **attenuation** in the **spanwise** direction.

Case ($St_\eta = 0.19$, $M = 0.5$)



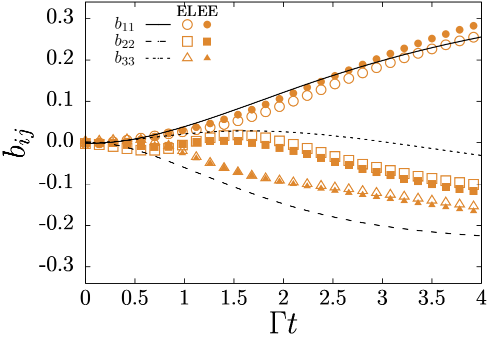
Case ($St_\eta = 0.19$, $M = 0.5$)



- **Weaker decrease** of growth rates of TKE and dissipation rate.
- Less turbulence **attenuation** with increasing M.

Case ($St_\eta = 0.19$, $M = 0.5$)

$$b_{ij} = \langle u_i u_j \rangle / \langle u_i u_i \rangle - \delta_{ij}/3$$



- Significant increase in b_{22} (gravity direction).
- Higher mass loading leads to **more energy transfer** in the gravity direction, **reducing** the turbulence attenuation.

Conclusion

- Homogeneously sheared turbulence (HST): a **test-bed** for turbulence models
- The dispersed phase may **enhance** or **attenuate** turbulence.
  - **No modulation** for small Stokes number ($St_\eta = 0.06$) and small mass loading ($M = 0.125$).
  - **Turbulence enhancement** for small Stokes number ($St_\eta = 0.06$) and high mass loading ($M = 0.5$).
  - **Turbulence attenuation** for larger Stokes number ($St_\eta = 0.19$). The strongest attenuation is for the small mass loading ($M = 0.125$).
- Excellent agreement between **Eulerian-Eulerian** and **Eulerian-Lagrangian** simulations.
- Kinetic based Eulerian-Eulerian model with **Anisotropic-Maxwellian/Gaussian** closure verified in the **semi-dilute regime**.